FRG19- Large: A Novel Bioenergy System for Marginal Environments

1. PROJECT ABSTRACT
This project aims at developing a novel biomass conversion process using renewable and sustainable energy sources. The project falls within the AUS “Bioscience and Bioengineering research institute (BBRI)” research track on “Biomass and Biofuels”. The concept involves the utilization of concentrated solar power (CSP) in delivering the energy demand of an intensive biomass conversion process to produce high quality biofuels (hydrogen-rich gas and bio-oil) and biochar. The biomass materials to be investigated will include Salicornia and food waste. The former is a type of halophyte that has great potentials as a feedstock for biofuel and has been field tested at large scale under the harsh desert environment in the UAE (ICBA). The latter is radially available everywhere and is in particular posing a major concern in the UAE where 38% of the food prepared daily goes into waste. In principle, the biofuels produced can be used for electricity generation via hydrogen fuel cells, gas/steam turbines and internal combustion engines, while the process by-product, which is biochar, can be highly useful in enhancing the desert soil in the UAE (fertilizer). The overall proposed concept will be built on a recent paper (Bashir et al., 2017) and two patented concepts by the PI (PCT/GB2013/051429 and PCT/GB2014/051358) on integrated solar thermal biomass conversion, CO$_2$ capture and waste treatment. The proposed concept is expected to be highly competitive to existing biomass thermal conversion systems, with a factor close to 50% improvement in the overall efficiency with the added advantages of addressing the environmental problems associated with waste disposal. If realized, this will revolutionize processes for thermal conversion of biomass, particularly in marginal environments of high salinity and solar radiation, such as in the Middle East and North Africa (see Fig. 1).

The main goal of this project is to provide a proof of concept for a cost effective and technically feasible modern bioenergy system through experimentation, theoretical modelling, thermo-economic and a demonstrated test rig. The project outcomes are expected to help in achieving the UAE target to generate 44 per cent of power from renewables by 2050, as well as establishing the UAE competitiveness in R&D of solar assisted thermal conversion processes. In addition to the technical and scientific objectives, the project will also include training of researchers on the proposed technology and access to advanced labs at leading research institutions in the UK.

The proposed project duration is 36 months with a total budget of AED 998,000. The project consortium will include, in addition to the AUS researchers, a UAE based international non-profit research center and four international experts in mathematic modeling, solar thermal conversion and bioenergy technologies from three different reputed UK universities.
2. PAST AUS PROPOSALS & AWARDS

Table 1. Summary of AUS Faculty Research Grants (FRG) proposals

<table>
<thead>
<tr>
<th>Program</th>
<th>Role (PI/Co-I)</th>
<th>Project Title</th>
<th>Requested Funding</th>
<th>Status (Awarded/Declined)</th>
<th>Amount Awarded*</th>
<th>Current Status (Active/Complete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBRI18-CEN-12</td>
<td>PI</td>
<td>Characterization of Temperature/Saline Tolerant Microalgae for Biochar and Biofuel Commercialization</td>
<td>735,700</td>
<td>Declined</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EFRG18-BBR-CEN-050</td>
<td>PI</td>
<td>production of biofuels from the Algae</td>
<td>149,430</td>
<td>Awarded</td>
<td>149,430</td>
<td>Active</td>
</tr>
<tr>
<td>EFRG18-BBR-CEN-06</td>
<td>PI</td>
<td>Modelling and simulation of a novel conversion of paper waste</td>
<td>75,000</td>
<td>Awarded</td>
<td>75,000</td>
<td>Active</td>
</tr>
<tr>
<td>EFRG18-BBR-CEN-050</td>
<td>PI</td>
<td>production of biofuels from the Algae</td>
<td>149,430</td>
<td>Awarded</td>
<td>149,430</td>
<td>Active</td>
</tr>
<tr>
<td>FRG16-R-27</td>
<td>PI</td>
<td>Thermochemical conversion of date palm tree waste to hydrogen-rich fuel</td>
<td>88,000</td>
<td>Awarded</td>
<td>88,000</td>
<td>Completed</td>
</tr>
</tbody>
</table>

* Currency: AED

3. CAREER SCHOLARLY AND ACADEMIC IMPACT

I am a certified Chemical Engineer with over 25 years of academic and industrial experiences. I am also a member/fellow of several UK’s professional bodies (see the CV). I joined the AUS as Associate Professor of Chemical Engineering in Aug 2015. Before that, I held various academic positions for 12 years with leading universities in the UK (Heriot-Watt, Edinburgh, Sheffield and Aston). Prior to my academic career, I spent around 8 years (1992-2000) serving the oil/gas industry in the Middle East. Further details on my experience and academic background can be found in the CV and in my personal web links below:

https://www.aus.edu/faculty/dryassir-taha-makkawi
https://www.aus.edu/bioenergy-and-solar-conversion-research-group

Details of my current scholarly and academic impact can be found at the web links below:

https://scholar.google.com/citations?hl=en&user=M4b0qWAAAAAJ&view_op=list_works&sortby=pubdate
https://www.researchgate.net/profile/Yassir_Makkawi

My current research is focused on Biomass and Biofuels. This falls within the AUS research theme under the Biosciences & Bioengineering Research Institute (BBRI). I am also currently establishing the AUS center of excellence (CoE) in solar-thermal conversion processes, with financial support from the UK government. During the past five years, I have been consistently contributing top quality research and scientific papers published in top journals of high impact factors (IF 3.0–6.2). I raised high research income and established research groups (see Fig. 2 and Table 1) at two different Universities; mainly working on projects related to computational modeling of fluidization, multiphase flow reactors and biomass pyrolysis and gasification. After
joining the AUS in Aug 2015, I establish the AUS first research group on solar conversion and bioenergy (https://www.aus.edu/bioenergy-and-solar-conversion-research-group). All of the current on-going research is of multi-disciplinary nature and involves collaboration with various international research groups and UAE academic and industry.

* 1 USD ~ 3.7 AED

Fig. 2. Summary of research income, research groups and publications during the past five years

Table 2. Summary of the recent research grants

<table>
<thead>
<tr>
<th>Duration</th>
<th>Project title</th>
<th>Funding source</th>
<th>PI</th>
<th>Fund (AED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun 18–May 19</td>
<td>Modelling and simulation of a novel conversion of paper waste</td>
<td>AUS FRG’ 2018</td>
<td>Makkawi</td>
<td>75,000</td>
</tr>
<tr>
<td>Jun 18–May 20</td>
<td>production of bio-fuels from the Algae</td>
<td>AUS EFRG 2018</td>
<td>Makkawi</td>
<td>149,430</td>
</tr>
<tr>
<td>April 18–Mar 19</td>
<td>Solar conversion of waste to energy</td>
<td>BEIS- GSIKE’ (UK)</td>
<td>Makkawi</td>
<td>206,000</td>
</tr>
<tr>
<td>April 18–Mar 20</td>
<td>Production of acidic biochar</td>
<td>Industry, EGA’ (UAE)</td>
<td>Makkawi</td>
<td>635,000</td>
</tr>
<tr>
<td>Jun 16–May 18</td>
<td>Conversion of date palm waste</td>
<td>AUS FRG’ 2016</td>
<td>Makkawi</td>
<td>88,000</td>
</tr>
<tr>
<td>Jan 2016</td>
<td>Development of a novel reactor</td>
<td>AUS Start-up grant</td>
<td>Makkawi</td>
<td>12,000</td>
</tr>
<tr>
<td>Feb 2015</td>
<td>International link</td>
<td>Newton Fund, UK</td>
<td>Makkawi</td>
<td>10000</td>
</tr>
<tr>
<td>April 15–Mar 17</td>
<td>EPSRC (with Glasgow University)</td>
<td>EPSRC’</td>
<td>Makkawi</td>
<td>1755,000</td>
</tr>
<tr>
<td>Oct 14–Sep 16</td>
<td>Paper waste to high value products</td>
<td>Industry, UK</td>
<td>Makkawi</td>
<td>1215,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>4,145,430</strong></td>
</tr>
</tbody>
</table>

* FRG: faculty research grant; BEIS: Gulf, Science, Innovation and Knowledge Economy; GSIKE: UK Department for Business, Energy and Industrial Strategy; EGA: Emirates Global Aluminum; FRG: faculty research grant; EPSRC: UK Engineering and physical research council

During the past five years, I led various large multidiscipline research teams (mechanical, electronic, mathematic, chemistry and power) including researchers from AUS and various UK universities, in order to solve challenging problem related to bioenergy technology. Beside the scientific and technology development, most of these projects involved training students on computational modeling and building of new experimental facilities. As part of this, I developed two innovative concepts on biomass thermochemical conversion processes. The first concept involves the conversion of biomass to fuel gas using a novel approach utilizing solar thermal with CO₂ capture. A patent on this has been filled in 2013 with an international application number PCT/GB2013/051429 under the title “process and apparatus for thermochemical conversion”. The second concept involves the conversion of paper industry solid waste into a clean fuel gas. This has also been filled with an international patent number PCT/GB2014/051358 under the title "Syngas production from paper mill waste”. Related to these, a third patent on novel solar-thermal conversion reactor is currently under preparation for internal approval.
4. PROJECT DESCRIPTION

4.1. Introduction
Recently, the International Energy Agency (IEA) reported that bioenergy would have the biggest growth in renewable resources between 2018 and 2023 (IEA’s Renewables 2018). The great potentials lies on the use of biofuels in the industry, electricity generation, hydrogen energy and transportation sectors. The use of waste biomass and organic residues for biofuels is particularly attractive as it offers a solution to mitigate concern over land use for energy crops besides addressing environmental problems associated with contamination of waste and soil by landfill. In addition, biomass conversion to biofuels produces biochar as a by-product biochar, hence expanding the benefit of biomass energy to countering land degradation and enhancing the soil, especially in desert regions such as the middle east and North Africa in general and in the Gulf region in particular.

In this project, we are proposing a novel technology that combines the two most abundant energy resources, which are solar and biomass. One of the basic paths to do so is the so-called “solar thermochemical process.” Solar thermochemical conversion of biomass can provide long-term solar storage while converting the chemicals to high-density fuels. Historically, the earliest attempts on solar-biomass conversion goes back to the mid 1970s. Antal (1978a, 1978b, 1979) carried out first attempts on biomass fast and slow pyrolysis under various concentrated solar radiation intensities. Further studies carried out during the 1990s demonstrated the potentials of this method in converting various biomass feedstock in different types of solar reactors (e.g. Ingel et al., 1992) to produce biofuels and chemicals. With the recent growing demand of clean energy and the strict environmental rules, there is now renewed interest and more acceptance of solar-thermal conversion of biomass as a modern concept for bioenergy.

Here, it is proposed to utilize concentrated solar-thermal to drive the endothermic biomass pyrolysis reaction in a novel tubular reactor. This produces high-density energy in the form of bio-oil and fuel gas in addition to biochar. Following this, it is proposed to integrate a biomass steam gasifier, where the Biochar will be utilized along with a fresh feed biomass to produce hydrogen-rich gas in the gasifier. The combined system will produce high value products (hydrogen-rich gas, bio-oil and char) with zero by-products. The type of biomasses to be investigated include waste food and a halophytic plant that holds specific interesting characteristics that of relevance to improving and upgrading the gas and biochar qualities. The specific technical work will include development, through modeling, experimentation and thermos-economic analysis of a modern bioenergy system that, in addition to biofuel and char production, encompasses in situ CO₂ capture and tar elimination in the gasifier. Hydrogen or hydrogen-rich fuel and bio-oil are widely accepted as a future key energy source (e.g. with fuel cells), while the biochar is commonly used in soil amendment. In this project, the product bio-oil and hydrogen-rich gas will be tested for power generation using internal combustion engine and solid-oxide fuel cell, respectively. The project will also include training of researchers on state of the art instruments at the collaborators facilities in the UK.

4.2. Track
This project will provide a proof of concept to progress the development of a novel biomass and bioenergy technology. It is directly relevant to the AUS track on Biosciences & Bioengineering Research Institute (BBRI), which encompasses the field of biomass, bioenergy and biofuels. The
biofuels produced from non-food-based biomass and waste organic matters are particularly very attractive for industry and is currently receiving increasing attention around the world. It offers renewable energy as well as addresses the environmental concerns associated with waste disposal. Furthermore, the integration of such process with solar thermal offers another advantage of tremendous improve in the process efficiency. Nevertheless, this option has not yet been well explored in the UAE and the Gulf region in general.

In this project, the proposed experiments and modelling will strengthen the BBRI track at the AUS by establishing expertise in computer modeling and experimental investigation of biomass pyrolysis and gasification, which are essential parts of bioenergy research. This project will also open the doors for wider collaborations between the BBRI and other disciplines within AUS and beyond. Furthermore, this will strengthen external collaborators with four researchers from three different UK universities, who are already collaborating with the PI, as co-investigators, on two different externally funded projects. The researchers involved will also benefit from the PI’s existing biomass thermal conversion lab and computational facilities, were the latter includes a powerful workstation of 12 core processors and state of the art software for multiphase flow reactive systems (ANSYS Fluent CFD code Ver 19.1). Besides, this will be an excellent opportunity to train postdocs and MSc students on such a fast developing renewable energy technology.

4.3. Goals & Objectives
This is a multi-theme project where knowledge of biomass pyrolysis/gasification, concentrated solar-thermal power, biochar and mathematical modelling are brought together in order to develop an innovative and a sustainable process for the production of biofuels and biochar. The biomass feedstocks consist of two different organic matter, namely, food waste and Salicornia. The latter is a halophyte well-adapted for the high salinity and hot climate desert in the UAE. The ultimate goal is to provide a proof of concept for a cost effective and technically feasible bioenergy system through theoretical modelling, experimentation, thermo-economic analysis and demonstration unit. The specific scientific and technical objectives are:

- Modify a set of existing Computational Fluid Dynamic (CFD) models to simulate the hydrodynamics and thermochemical behavior of a novel pyrolysis and gasification reactors.
- Design and build of a novel tubular reactor for biomass pyrolysis
- Design and build of an outdoor demonstration unit of a modern bioenergy system.
- Experiments of biomass pyrolysis in a lab-scale novel reactor using conventional heating (electric furnace) and concentrated solar thermal.
- Experiments of biomass steam gasification in a lab-scale fluidized bed reactor.
- Detailed analysis of the product biofuels (liquid oil and gas) and biochar.
- Out-door experimentation on a demonstration rig of the proposed closed loop system under solar-thermal.
- Parametric analysis through experiments to maximize bio-oil yield and optimize the quality and production of a clean hydrogen-rich gas and biochar.
- Test of the produced bio-oil and hydrogen-rich gas in a combustion engine and a solid oxide fuel cell, respectively.
- Thermo-economic analysis of the closed loop system to help in exploitation of commercialization potentials.
4.4. **Broader Impacts of the Project**

The outcome of this project is believed to have a high impact in future development of modern biotechnology and renewable energies in the UAE by:

- Providing the expertise in an area that escaped satisfactory attention, despite of being highly relevant to the UAE and the Gulf region in general, that is solar-thermal conversion processes.
- Informing the energy policy makers and the industrial sector of the fruitfulness of bioenergy and its importance for diversity in energy supplies, especially in the UAE and the Gulf region.
- Establishing the UAE competitiveness in R&D of renewable energies and training the next generation of scientists and researchers on modern bioenergy.
- Support the potential development of decentralized modern bioenergy system on sites for waste management facilities (see for the example the provided letter of support).

On a wider level, the outcomes of this project will contribute to the global effort on fighting climate change and global warming by offering a technically and economically feasible concept of modern bioenergy system. It is also hoped that the outcomes of this project will set the scene for wider application of solar assisted thermochemical conversion processes, especially in marginal environments.

4.5. **Proposed Research**

The research proposed here involves solar-thermal biomass pyrolysis and steam gasification with in situ gas cleaning in a single closed loop system. The combined process is expected to produce high quality fuels (liquid bio-oil and hydrogen-rich gas) for power generation/industry use, in addition to biochar/ash suitable for the use in the soil amendment (fertilizer). This is described in three main concepts as indicated and detailed below.

4.5.1. **Concept 1: Solar-Thermal Pyrolysis**

Fig. 3 shows details the proposed novel pyrolysis process utilizing concentrated solar thermal to derive the highly endothermic biomass pyrolysis reaction. This consists of a tubular reactor/receiver where a particulate phase of biomass (Salicornia and/or fish waste) undergoes rapid thermal conversion driven by a concentrated solar-thermal. In order to maintain uniform temperature distribution, the tubular reactor will be arranged at the focal point of a parabolic trough concentrator. Previously, the PI and his research team studied through theoretical modeling the performance and products yield in a similar pyrolysis system. For the operating conditions considered the study confirmed great potentials of the solar reactor with bio-oil yield of 51.5%, 43.7% biochar, and 4.8% non-condensable gas (Bashir et al., 2017). However, it was also observed that flow non-uniformity might occur at high particulate flow due to gravity settling of the biomass particles at the lower boundary, which in turn may result in static or slow moving solid layer at the bottom of the reactor. In actual pyrolysis reactor, such a behavior carries the risk of increased pressure and static zones or complete blockage of the reactor, hence, drastically affecting the pyrolysis process. Accordingly, it is proposed here to use a modified and novel tubular reactor to improve the flow characteristics and enhance the products yield. Our recent study (unpublished) on a cold flow model of this reactor has confirmed substantial improvement in the biomass flow distribution (see the data shown as part of Fig. 3) with the added advantage of improved gas residence time, a parameter that is essentially important to control in order to achieve high bio-oil yield. The details of this novel reactor are described in point (b) of this section.
In biomass pyrolysis, the thermochemical conversion process mainly produces solid and primary pyrolysis gas according to the following simple one reaction model:

\[
\text{Biomass (C) + heat} \rightarrow \text{Char + Pyrolysis gases (CO, CO}_2, \text{H}_2\text{O, CH}_4, \text{H}_2, \text{Tar}) \quad (1)
\]

Following rapid cooling (quenching), the heavy hydrocarbons (Tar) in the pyrolysis gas condenses to produce what is commonly refer to as bio-oil, while the non-condensable gas mainly consist of light hydrocarbons (CO, CO\(_2\), H\(_2\)O, CH\(_4\), H\(_2\)).

(a) **Pyrolysis feedstocks**

The biomass feedstocks for the pyrolysis part of the process are halophyte Salicornia and fish waste. The choice of these organic matters have been made based on the following:

1. Halophyte Salicornia:
   i. Salicornia bigelovii is a multi-purpose highly salt-tolerant plant that can be used as fresh vegetable, animal forage and biofuel production. It is currently experimentally grown at large scale in an experimental station of the International Center for Biosaline Agriculture (ICBA) in Dubai (UAE) and at a coastal desert area in the Emirate of Umm Al Quwain. ICBA team run experiments on Salicornia utilizing low-quality water resources such as saline groundwater reject brine from desalination, aquaculture effluents and seawater. Studies by the project collaborator from ICBA, Dr Lyra, have confirmed the great potentials of Salicornia growth under various water salinity up to full strength seawater (Lyra et al. 2016). The fresh biomass can reach 140 t/ha and seed yield 3.5 t/ha. The plant seeds are found to have high oil content (30%) and show qualitative and quantitative characteristics similar to those of the seeds of other bioenergy crops, such as canola and safflower.
ii. Our recent analysis (not published) of Salicornia have shown that it contains considerably high ash content with high concentration of alkali earth metals (see Fig 4). This is not surprising given the fact that this plant is irrigated by high salinity seawater. Upon pyrolysis, these metals will end up in the biochar. While this may negatively affect the bio-oil yield by catalytically cracking the pyrolysis gas, it is of great interest in the context of the proposed gasification, since the rich-metal biochar can serve as a catalyst and adsorbent in the gasifier, as will be discussed later.

(2) Fish waste

i. The UEA and the gulf region at a wide are nowadays experiencing massive investment in the fishing industry to satisfy the increase in demand. The UAE is also developing inland and coastal fish farming programs. As a result, the amount of waste coming from the fishing industry is increasing. According to our own recent survey, the amount of fish waste in one of Sharjah’s fish market only is nearly 500 tons per year. Clearly, the disposal of such quantity overall the UAE requires the development of cost effective and environmental friendly disposal method, as proposed here.

ii. As shown in Fig. 4, the proposed fish waste (dead salmon and seabass) have shown this feedstock to share some of the interesting characteristics of the Salicornia in terms of high ash content. The concentration of calcium is particularly high. This makes the biochar produced from fish waste more appealing for CO$_2$ capture. Several studies, (e.g. Hayashi, 2002 and Sathe, 2003; Hwang and Mebel, 2000, Corella et al., 2008) reported that the inherent content of such compound in the biochar can be useful in CO$_2$ capture.

It is also interesting to note that processing of the two identified feedstocks hold another promising feature. Calcium and Magnesium atoms and their carbonated forms, commonly referred to as Dolomite [CaMg(CO$_3$)$_2$], have been widely reported for their high potentials in catalytic cracking of tar in biomass gasification (e.g. Ref Mohammed et al., 2013; Mukherjee, 2011; Vassilatos et al., 1992). This is of relevance to the proposed gasification part of the closed loop process, as will be discussed later.

(b) Pyrolysis reactor

The proposed lab-scale experimental reactor to be used for the pyrolysis comprises a novel tubular fluidized bed reactor (patent application under process) connected to a biomass feeding system and gas cooling/condensation system. The latter, which are shown in the red box, are currently existing in the AUS lab as part of an augur pyrolysis reactor (see Fig. 5). The novel aspects of the proposed tubular reactor lies on the following:

i. The reactor orientation and the design of the lower perforated plate (see the bottom left corner in Fig. 3) will allow for phase separation by creating a layer of fast velocity gas moving over a
slower suspended solid (biomass/char). This is ideal for limiting the direct contact between the biochar and the pyrolysis gas, hence, limiting the effect of biochar catalytic cracking.

ii. In a solar heating by parabolic trough, the flow structure, described in point i above, will have an added advantage by creating higher temperature at the lower layer of the suspended biomass/char while the top pyrolysis gas remain at a relatively lower temperature, hence, increasing the bio-oil yield by limiting the effect of thermal cracking.

iii. Slight inclination in the reactor tube (i.e. around 10–20 degrees to the horizontal) will allow fluidization at a gas flow rate below the minimum fluidization velocity, hence, considerably limiting the flow of the fluidizing or sweeping gas (usually nitrogen).

(c) Pyrolysis operating condition and products analysis

The pyrolysis experiment will be carried in a horizontal tubular reactor of around 2.5 cm diameter and 3 m length. The experiments will be carried in-door using an existing set-up with electric furnace heating (see Fig. 5) and outdoor using a new set-up of a parabolic solar concentrator as shown in Fig. 4. This will allow drawing conclusion and conducting comparative techno-economic analysis of the reactor performance under the conventional electric heating and concentrated solar thermal.

The reactor will be fully automated including instrumentation and data logging of temperature, pressure and gas flow rates. Prior to the pyrolysis experiments, the biomass feedstocks will be grounded and dried to reduce the size and moisture content below 10 wt%. The Salicornia will be open-air sun dried at an average outdoor temperature of around 30–45 °C. The fish waste will be processed externally (local food processing company) using a food grinder/dehydrator operating at 80 °C. It is proposed to run the pyrolysis experiments within the temperature range of 300–600 °C with the biomass feeding rate in the range of 0.2–1 kg/h. The produced bio-oil and biochar will be collected and stored for later analysis while the non-condensable gas will be quantified and analyzed online before flaring and disposing to open atmosphere.

![Existing auger reactor to be used for in-door testing after replacing the auger screw tube with the proposed solar-thermal receiver/reactor shown in Fig. 2.](image-url)
4.5.2. Concept 2: gasification with in situ tar cracking and CO₂ capture

Fig. 6 shows details of the second part of the proposed closed loop bioenergy system. This consists of a fluidized bed reactor equipped with two cyclones, hot gas filter, condenser and a gas sampling line. The reactor will be fluidized by steam and operated at a temperature >650 °C to produce a high quality H₂-rich gas. The cyclones will be used for the separation of the biochar/ash. In a conventional steam gasifier, the process produces a solid phase (char/ash) and product gas mainly consists of CO, CO₂, CH₄, H₂ and CH₄ and a small fraction of tar (heavy hydrocarbons). The main reaction model is as follows:

\[
\text{Biomass (C) + heat} \rightarrow \text{ash + char + Pyrolysis gases (CO, CO₂, H₂O, CH₄, H₂, Tar)} \quad (2)
\]
\[
\text{C + H₂O} \rightarrow \text{CO + H₂} \quad (3)
\]
\[
\text{C + CO₂} \rightarrow 2 \text{CO} \quad (4)
\]
\[
\text{C +2H₂} \rightarrow \text{CH₄} \quad (5)
\]
\[
\text{CO + H₂O} \rightleftharpoons \text{CO₂ + H₂} \quad (6)
\]
\[
\text{CO₂ + CH₄} \rightarrow 2\text{CO + 2H₂} \quad (7)
\]
\[
\text{CH₄ + 2H₂O} \rightarrow \text{CO₂ + 4H₂} \quad (8)
\]

The choice of steam as the fluidizing medium is made to promote the hydrogen production, mainly through water-gas shift reaction (Eq. 6) and limit the contamination of the product gas by nitrogen. Conventionally, in biomass steam gasification, the highly endothermic pyrolysis phase of the reaction is driven by partial combustion of the solid fuel when fluidized by air. The solid material consumed in the combustion may reach up to 40 % of the total feed and the gas heating value would be low, as a result of nitrogen dilution. On the other hand, the CO₂ level would high, in the range of 25-50 vol% on dry basis. Furthermore, the gas produce usually contains high levels of tar, which must be considerably reduced to avoid any downstream problems. In this project, a novel approach will be investigated to develop sustainable gasification, gas cleaning and tar elimination without the reliance on any external energy sources.

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Fig. 6. Proposed steam gasification for the production of H₂-rich gas and biochar/ash.
(a) *Gasification feedstocks*

The proposed biomass feedstock for the gasification experiments is a local food waste. The main reason for this choice is based on the following:

- Food waste is readily available everywhere and in particular posing a major concern in the UAE where 38% of the daily food goes into waste.
- Our recent analysis of local food wastes (collected from various restaurants in the UAE) have shown that this feedstock is of low ash and pH (acidic) compared to the various waste organic biomass available in the UAE (see Fig. 3-a and Fig. 7). Therefore, the particulate phase produced in the gasifier is expected to be of low pH value, thus, suitable to neutralize the highly alkaline biochar produced in the pyrolysis reactor. Such a neutral biochar will be valuable for the soil enhancement (fertilizer) in the sandy desert in UAE, as discussed earlier.

(b) *Tar cracking and CO₂ capturing by biochar*

As noted earlier, formation of tars during biomass gasification is a critical problem in downstream processing and in the use of the product gas for electricity generation. In a fluidized bed biomass gasifier operating at a temperature within the range of < 900 °C, the typical tar content in the gas is in the range of 1-3 g/Nm³ on dry gas. This is well above the maximum recommended limit for safe operation of most internal combustion engines (less than 100 mg/Nm³) [Iversen, 2004].

Currently the most widely used methods for tar elimination include: (1) wet scrubbing, which entails environmental problems because of the large quantities of condensate, and (2) dry catalytic cracking, which, while minimizing the by-products and increases the H₂ yield, is expensive and catalysts are prone to rapid deactivation.

It is noted earlier that the Salicornia and fish waste feedstocks (proposed for the pyrolysis experiment) contain high fractions of alkali metals, which upon pyrolysis are expected to end up in the biochar. Of particular interest here are the Ca, and Mg. At a temperature within <800 °C, and in the absence of oxygen, these metals undergo a chemisorption reaction to eliminate the CO₂ according to the following reactions [Hwang and Mebel, 2000]:

\[
\begin{align*}
\text{Ca reaction} \\
\text{Ca (s) + CO}_2(g) & \leftrightarrow \text{CaO (s) + CO (g)} & (9) \\
\text{CaO (s) + CO}_2(g) & \leftrightarrow \text{CaCO}_3(s) & (10) \\
\text{Mg reaction} \\
\text{Mg (s) + CO}_2(g) & \leftrightarrow \text{MgO (s) + CO (g)} & (11) \\
\text{MgO (s) + CO}_2(g) & \leftrightarrow \text{MgCO}_3(s) & (12)
\end{align*}
\]

More interestingly, Mg and Ca and their carbonated forms are expected to greatly resemble the catalytic effect of dolomite in biomass gasification. Dolomite [CaMg(CO₃)²] is reported to achieve between 65–100 % tar cracking. The exact tar cracking mechanism is still a subject of research.
but it is generally understood to proceed to produce lighter hydrocarbons via the following reaction [Gerber et al., 2010]:
\[ \text{Tar} \rightarrow n_1\text{CO} + n_2\text{CO}_2 + n_3\text{H}_2\text{O} + n_4\text{CH}_4 + n_5\text{H}_2 \] (13)

Therefore, in this concept, in addition to heating the reactor, the solid biochar produced in the pyrolysis reactor will also serve in (i) eliminating CO\(_2\) from the product gas, mainly by carbonation as described by Eqs. 9–12 (ii) improving the product gas quality by catalytic cracking of heavy hydrocarbon (tars) as described by Eq. 13.

(c) Gasifier operating condition and products analysis
The experimental gasifier will be operated to process a mixture of hot biochar and fresh feed of dry particulate food waste. Similar to the proposed biomass pretreatment for the pyrolysis, the food waste will be processed at a local company for grinding and dehydrator at 80 °C. The gasifier will be operated within the temperature range of 650–800 °C. To ensure maintaining the reactor at the required temperature, the feeding rate of the food waste will be relatively low compared to the flow of the hot biochar while the steam flow rate will be adjusted to ensure sufficient particulate flow as well as temperature. The gas exiting the reactor will pass through two cyclones, hot filter and condenser before being flared and disposed to the atmosphere. A sample of the final as will be sent for composition and tar analysis using an online GC and a set of impinger bottles, as per the guideline method [W. van de Kamp et al., 2005], respectively. The char/ash will be collected to access its potential application as a fertilizer.

4.5.3. Concept 3: Closed loop solar thermal conversion system
Fig. 8 shows the overall closed loop concept. Here, the above-described concepts 1 and 2 are integrated in a novel way to develop a modern bioenergy system utilizing concentrated solar radiation. The process produces bio-oil, H\(_2\)-rich fuel gas and biochar in a single closed loop. The main novel aspects of this concept are:

![Diagram of Concept 3](image-url)
• Integration of concentrated solar-thermal in a bioenergy system for the production of liquid bio-oil, fuel gas and biochar with zero emissions and zero by-products.

• Development of a new solar thermal receiver/reactor with novel fluidization method for thermochemical conversion of biomass and wider similar applications.

• Utilization of various biomass feedstocks of complementing characteristics for sustainable production of clean and sustainable biofuels and biochar.

• In principle, the process can be operated without disturbance during low solar radiation period and at night by using the pyrolysis non-condensable gas or fraction of the produced H₂-rich gas and liquid bio-oil for heating the pyrolysis reactor and raising steam for the gasifier. Thus, addressing one of the major challenges in solar related energy technologies.

4.5.4. Analysis of biochar and ash from pyrolysis and gasification reactors

The biochar will be subjected to a range of physical and chemical analysis in order to understand the qualities of the particulates (biochar and ash) produced during the pyrolysis and gasification process. The char produces from the pyrolysis will serve as catalyst and CO₂ capture, as described earlier, while the char/ash produced from the gasifier are expected to hold qualities to serve in soil amendment. The assessment will be focused on proximate/ultimate analysis, measuring the major metal elements (e.g. Ca, Fe, K, Mg and Na) and acidity (pH). The biochar/ash from the gasifier will be sent to the collaborator at Edinburgh University for further analysis relevance to the proposed soil application. This analysis will include water retention capacity, cation exchange capacity (CEC) and measurement of the interaction of biochar with soil in terms of pH and O₂ exchange using state of the art Planar optodes technique (see Fig. 9). In relation to this, it is worth noting that the PI and the co-investigator from Edinburgh University, Dr Masek, are currently collaborating on a similar work as part of another project on the acidic biochar.

4.5.5. Analysis of bio-oil and test in internal combustion engine

The physical and chemical properties of the biofuels produced from the Halophyte Salicornia and food waste biomass or/and their mixture will be measured to assess the quality of the biofuels. The properties of the biofuels will be compared with the standard fossil diesel properties. Due to the possible high viscosities and low calorific values, the biofuel may need to be upgraded in order to be used in diesel engines. Previously, the Co-investigator from Aston University (Hossain et al. 2016, Hossain et al. 2013) carried out studies on using blend of pyrolysis oils and biodiesel in a compression ignition engine. In this study, samples of the bio-oil will be sent to the collaborators at Aston University, where various single-phase biofuel blends will be prepared and tested in a three cylinder engine manufactured by Lister Petter (UK). The schematic diagram of the existing test rig at Aston University lab is shown in Fig. 10. In order to assess the engine load and emission, an eddy current dynamometer (Froude Hofmann AG80HS) will be used to measure and adjust the engine load and a five-gas emission analyzer and smoke opacity meter will be used to analyze the exhaust gas components and
measure the smoke intensity, respectively. The properties and performance of the bio-oil will be compared to the standard fossil diesel.

4.5.6. Test of hydrogen-rich gas in a solid oxide fuel cell

It is proposed to investigate the potentials of the hydrogen-rich gas produced in the gasifier as a fuel in a solid oxide fuel cell (SOFC) operating at atmospheric pressure. The use of hydrogen-rich gas and syngas from biomass gasification in SOFC have been reported in the literature [6-7] as well as being demonstrated at large plant power generation (Deya, et al., 2014; Cheddie, 2010; Doherty et al., 2010; Ghosh and De, 2006). By virtue of their operating temperature (600-800 °C), the SOFC are characterized by their rapid kinetics and high power generation compared to other types of fuel cells. The fuel cell is composed of the anode, cathode and the electrolyte that separates both electrodes. The electrolyte in SOFC will be a nonporous metal oxide (Y$_2$O$_3$-stabilized zirconia) while the anodes and cathodes are of nickel and Sr-doped LaMnO$_3$, respectively. The operating principles of the SOFC and the reactions at the anode and cathode are described in Fig. 11.

4.6. Work Plan

4.6.1. Summary of the project team and work plan

The detailed timeline of the project work plan is given in Table 3. The responsibility of the project management and execution of the work plan will solely lie on the Principal Investigator (PI), Dr. Yassir Makkawi. The project team will include, in addition the PI:
Internal AUS Co-investigators
- Prof Prof. Mohamed Gadalla – Mechanical Engineering
- Dr Yehya Elsayed – Biology, Chemistry & Environmental Sciences
- Dr Amani Al-Othman - Chemical Engineering

External Co-investigators
- Prof Raffaella Ocone – Chemical Engineering, Heriot-Watt University (HWU), UK.
- Dr Ondrej Masek – Engineering Systems (Earth Resources), University of Edinburgh (UoE), UK.
- Prof Philip Davies – Mechanical Engineering, Aston University (AUS), UK.
- Dr Abul Hossain – Mechanical Engineering, Aston University (AU), UK.
- Dr Dionysia-Angeliki Lyra (ICBA), Dubai.

Due to the ambitious plan and the high level of work involved, the project will include the following researchers, who will carry out the day-to-day activities:
- Two postdoctoral researchers
- One MSc qualifies researcher
- Two MSc students (sponsored by the AUS graduate school)
- Two undergraduate students (on hourly basics).
- Two external technicians (paid by ICBA)

The project team members will collectively contribute to the data analysis and dissemination of the results. The main experimental work will be carried out at the AUS facilities, with some analysis to be carried out at the collaborators facilities.

4.6.2. Work packages (WPs) and distribution of roles
WP 1: Computational fluid dynamic modeling
WP team: Dr Makkawi (AUS), Prof. Ocone (HWU), Postdoc-1 (AUS), MSc students 1 (AUS)
The objective of this work package is to develop a valid computational model for the simulation of the reactors (pyrolysis and gasification). These models will be used for the prediction of the products distribution and qualities and for sensitivity and scale-up study. The results will also be used for thermo-economic analyses as described in WP 8. The final validated models will be the corner stone for future development and design of the proposed bioenergy system. The researcher involved will benefit from previously models developed by the PI and the co-investigator on fluidized bed reactors, biomass pyrolysis and gasification (e.g. Hassan and Makkawi, 2018; Elewuwa and Makkawi, 2016; Makkawi and Ocone, 2006; Bashir et al., 2017; Yu et al., 2015). In this WP, the team will upgrade the existing models by adding user defined functions (UDF’s) to account for the effect of char catalytic cracking the pyrolysis reactor and CO₂ capture and tar cracking in the gasifier. The team will share the remote access to HWU computational facility as well as accessing the PI’s server (12 core processors workstation), which is uploaded with the latest version of ANSYS Fluent CFD code (Ver 19).

WP 2: Cultivation and supply of Salicornia
WP team: Dr Lyra (ICBA) and Dr Makkawi (AUS)
The objective of this work is to evaluate Salicornia biomass originating from different genotypes at open field-tested under different saline water applications. This will allow the project team to
identify the Salicornia genotype(s) that produce(s) the biomass with the best specifications and under which salinity treatment to get better products after the implementation of pyrolysis and gasification processes. The detailed work plan related to this work package includes:

- Different Salicornia genotypes will be cultivated at ICBA’s experimental station under 3 different water treatments: saline groundwater, reject brine from desalination and aquaculture water
- Selected high yielding Salicornia genotypes will be cultivated at a coastal desert area in Umm Al Quwain and irrigated with seawater
- The Salicornia biomass and seeds from the different genotypes will be collected at an advanced vegetative stage and will be given to AUS team for further analyses and study of biofuels production

**WP 3: Parabolic trough and solar reactor/receiver system**

**WP team:** Prof Gadalla (AUS), Dr Davies (AU), Dr Makkawi (AUS), MSc student 2 (AUS)

The objective of this work is to design/modify and test of (i) a novel solar reactor/receiver for biomass pyrolysis (ii) an optimized parabolic trough solar collector. The long experience of the investigator in solar thermal collectors and their applications in various processes will ensure development of a world experimental facility that produces accurate results. The specific detailed work plan related to the tubular solar receiver/reactor will include:

- Design, construction and commissioning of a lab-scale solar-thermal tubular reactor/receiver.
  This will be tested indoor under furnace heating (see Fig. 5) and at an outdoor set-up as shown in Figs 3.
- Integration and test of the lab-scale solar reactor/reactor with other components i.e. (i) pyrolysis set-up (ii) fluidized bed gasifier (ii) bio-oil, gas and biochar collection and analysis set-up (see Fig. 8)

The specific detailed work plan related to the solar reflector (parabolic trough) will include:

- Design and construct parabolic trough reflector and ray tracing
- Optimize the solar reflector for the solar reactor/reactor described above.
- Design and assembly of electronic control system with software for automated operation.
- Procurement and infrastructure planning for the outdoor demonstration facility.
- Data analysis and optimization, leading to overall evaluation of the integrated system.

It is worth noting that, large parts of the material required for the construction of the parabolic trough and tubular reactor/reactor are available in the AUS stores.

**WP 4: Pyrolysis experiments**

**WP team:** Dr Makkawi (AUS), Dr Elsayed (AUS), Dr Hossain (AU), Dr Masek (UoE), Postdoc-1 (AUS)

The main objectives of this work is to three folds (i) carry our indoor and outdoor pyrolysis experiments in a novel tubular reactor (ii) the work also involves optimization of the reactor to achieve maximum yield of bio-oil while marinating desirable features in the biochar (iii) test of the bio-oil in engine. The experiments will first be carried out indoor using an existing pyrolysis set-up with the heat supplied by an electric heater (furnace). This will then be followed by outdoor testing were the reactor tube will be placed at the focal point of a parabolic trough solar collector
in order to sustain the pyrolysis reaction by concentrated solar thermal. The data to be collected will include, but not limited, the following:

- Chemical composition of the bio-oil, non-condensable gas and biochar
- Heating value, Thermo-gravimetric profiles, bio-oil water
- Recommended operating condition (e.g. reactor temperature, biomass feeding rate)
- Products quantities for mass balance calculations.

Test of the bio-oil in an internal combustion engine will be carried out by the collaborator at Aston University as detailed earlier in Section 4.5.5 and in the collaboration plan Section 8.

WP 5: Gasification experiments
WP team: Dr Makkawi (AUS), Dr Elsayed (AUS), Dr Masek (UoE), Dr. Al-Othman (AUS), Researcher (AUS), Postdoc-2 (AUS)
This work mainly involve the design, commissioning and experiments on biomass steam gasification in a fluidized bed reactor. Food waste and Salicornia biochar will be used as the feedstocks. Part of the experiments will be carried out indoor using electric heaters while the outdoor tests will be conducted as part of the overall integrated demonstration unit. The clean product gas, which is expected to have high hydrogen content (>60 mol%) and almost free of CO₂, will be tested for potential application in a solid oxide fuel cell, as described in Section 4.5.6.

WP 6: CO₂ capture, tar elimination and test of fuel gas in fuel cell
WP team: D. Makkawi (AUS), Dr Elsayed (AUS), Dr. Al-Othman (AUS), Dr Masek (UoE), Researcher (AUS), Postdoc-2 (AUS)
This work will be include experimental analysis of the operating conditions, particularly, the gasifier temperature, fuel/char blend and fraction of cracking metals in the biochar. This will be related to the degree of tar and CO₂ elimination. The small-scale experimental set-up will allow for tar sampling and CO₂ analysis using the Guide Line Method and an online GC. The Postdoc researcher with close support from the PI will mainly conduct this part of the work, including the one described in WP 5. It is expected that, the outcome of this task will provide strong practical demonstration and scientific basis for the CO₂ capture and tar elimination in gasification using the proposed biomass feedstocks.

This work package will also include experimental study of the potential use of the product clean hydrogen-rich gas in power generation using a simple lab-scale solid oxide fuel cell as detailed earlier in Section 4.5.6 and in the collaboration plan Section 8.

WP 7: Demonstration test rig
WP team: Dr Makkawi (AUS), Dr Gadalla (AUS), Prof Davies, Postdoc-1 (AUS), Postdoc 2 (AUS), MSc student 2 (AUS)
The work activities described in WP1 and WP3–WP5 will all feed into this final activity where the pyrolysis and gasification reactors will be integrated to form a demonstration rig at an outdoor setting. The main aim of this WP is two folds: (i) highlight the feasibility of the proposed closed loop concept under real operating condition (ii) collection of the experimental data required for thermos-economic analysis in WP 8. Moreover, alternative process conditions and integration solutions (e.g. pyrolysis gas recirculation and solar steam generation) will be investigated and compared in terms of thermal efficiency and operational feasibility.
WP 8: Thermo-economic analyses
WP team: Prof Gadalla (AUS), Dr Davies (AU) and MSc student 2 (AUS)
A thermo-economic analysis of the integrated system including process unit of the novel closed loop bioenergy system will be performed to verify the process feasibility. This activity will require suitable specifications of the boundaries of the analysis and will be articulated in by inventory analysis to quantitatively analyze mass and energy inputs and outputs. Moreover, alternative process flowsheets with conventional heating will be developed and compared in terms of thermal efficiency and economic profitability.

WP 9: Project management
WP team: Dr Makkawi (AUS)
The responsibility of the project management and coordination will lie with the PI, Dr. Makkawi. This will include coordination of dissemination and publication of the results in national and international conference proceedings and refereed journals. It is proposed that the PI will have face-to-face meetings with the AUS researchers on a weekly basis; while meetings with the external collaborators will be conducted during the PI and collaborators exchange visits, and more frequently via emails and phone conference. Remote access to a main computer will be facilitated, where all parties can have access to the updated experimental and modeling results at all stages during the project execution. Upon completion on the major work, an exploitation of the commercialization potentials will be eventually carried out in consultation with the AUS research office. It is worth noting that the PI is currently collaborating with all of the named external collaborators through projects funded by the British Council (UK) and the UAE Industry.
Table 4. Detailed time table and specific tasks for work packages

<table>
<thead>
<tr>
<th>Work package and tasks</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<tr>
<td><strong>WP 1: Computational fluid dynamic modeling</strong></td>
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<td>1.1 Familiarization with the Ansys fluent CFD code</td>
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<td>1.2 UDF’s for CO\textsubscript{2} capture and tar cracking</td>
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<td>1.3 Implantation of the UDF’s in in reactive models</td>
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<td>1.4 Refining/validation of the models based on experimental data</td>
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<td><strong>WP 2: Cultivation and supply of Salicornia</strong></td>
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<td>2.1 Preparation of field and plantation</td>
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<td>2.2 Harvesting</td>
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<td>2.3 Mapping biofuel and biochar with feedstock type</td>
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<td><strong>WP 3: Parabolic trough and Solar reactor/receiver system</strong></td>
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<td>3.1 Procurement of components</td>
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<td>3.2 Design and manufacture of an optimized tubular reactor and parabolic trough system</td>
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<td>3.3 Infrastructure planning and preparation</td>
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<td>3.4 Installation of and integration of reactors and parabolic trough solar collector (PTSC)</td>
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<td>3.5 Leak tests and optimization</td>
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<td><strong>WP 4: Pyrolysis experiments</strong></td>
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<td>4.1 Familiarization with pyrolysis set-up</td>
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<td>4.2 Feedstock preparation and analysis</td>
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<td>4.3 Indoor experiments and data collection</td>
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<td>4.4 Outdoor experiments and data collection</td>
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<td>4.5 Products analysis</td>
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<td>4.6 Bio-oil engine test</td>
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<td><strong>WP 5: Gasification experiments</strong></td>
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<tr>
<td>5.1 Design and construction of reactor</td>
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<td>5.2 Feedstock preparation and analysis</td>
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<td>5.3 Indoor experiments and data collection</td>
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<td>5.5 Products analysis</td>
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<td><strong>WP 6: CO\textsubscript{2} capture, tar elimination and test of fuel gas in fuel cell</strong></td>
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<tr>
<td>6.1 Design and set-up of solid oxide fuel cell</td>
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<td>6.2 Gas and tar analysis</td>
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<td>6.3 Fuel cell experiments</td>
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<td><strong>WP 7: Demonstration test rig</strong></td>
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<td>7.1 Infrastructure and preparation of outdoor set-up</td>
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<td>7.2 Integrated pyrolysis and gasification reactors</td>
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<td>7.3 Closed loop experiments</td>
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<td>7.4 Data analysis and interpretation</td>
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<td><strong>WP 8 Thermo-economic analyses</strong></td>
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<td>8.1 Mass and energy balance analysis</td>
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<td>8.2 Comparative analysis</td>
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<td><strong>WP 9 Project management</strong></td>
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<td>9.1 Coordination and Financial management</td>
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<td>9.2 Dissemination and exploitation management</td>
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5. USE OF EXISTING AUS RESOURCES

Experimental resources
- Auger pyrolysis reactor- Pyrolysis experiment.
- Biomass feeding system- Feeding of biomass to the pyrolysis reactor.
- Pyrolysis gas quenching and cooling system- Collection of bio-oil.
- Cold flow model of a novel tubular reactor- Analysis of multiphase flow hydrodynamics.
- Gas chromatography-mass spectrometry (GC-MS)- Analysis of bio-oil chemical composition.
- Micro Gas Chromatography (MGC)- Analysis of hydrocarbon gas.
- Carbolite furnace- Indoor heating of pyrolysis reactor.
- Volumetric Karl Fischer (KF) titration- Analysis of water content in bio-oil.
- Thermographic analysis (TGA)- Analysis of thermal profile of biomass, biochar and bio-oil.
- CHNO analyzer- Ultimate analysis of the biomass and biochar.
- Inductively coupled plasma (ICP) spectrometer- Analysis of metal in biomass and biochar.
- Biomass grinder and Sieves/shaker

Computational resources
- Workstation of 12 core processors- Modeling of thermal conversion reactors.
- ANSYS Fluent CFD code- Modeling of multiphase flow reactive system

6. REFERENCES


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7. PI & Co-I BIOSKETCH

7.1. Principal Investigator Bio Sketch

Yassir Taha Makkawi
Associate professor of chemical engineering
Department of Chemical Engineering, American University of Sharjah
Tel: +971 6 5154938
E-mail: ymakkawi@aus.edu
Web page: https://www2.aus.edu/facultybios/profile.php?faculty=ymakkawi

(a) Professional Preparation
University of Khartoum (Sudan), Chemical Engineering BSc 1991
King Fahd University of Petroleum & Mineral (KSA), Chemical Engineering MSc 1995
Heriot-Watt University, Edinburgh (UK), Chemical Engineering Ph.D. 2003
Aston University, Birmingham (UK), Professional Practice in Higher Ed. Dip 2011

(b) Appointments
Associate Prof of Chemical Engineering, AUS, UAE 2015–present
Visiting Professor, European Bioenergy research Institute, UK 2015–2017
Lecturer and Senior Lecturer of Chemical Engineering, Aston University, UK 2008–2015
Teaching and Research Fellow, University of Sheffield, UK 2006–2008
Research Fellow, University of Edinburgh, UK Jun 2006–Nov 2006
Research Associate, Heriot-Watt University, UK 2003–2006
Sales and Tech Manager, Yaseah Oil/Gas Services and Supplies, UAE Jan 1999–Dec 1999

(c) Publications
(i) Top five most closely publications related to the proposed project
4. Mohamed Hassan and Yassir Makkawi, A hydrodynamic model for biomass gasification in a circulating fluidized bed riser, Chemical Engineering and Processing- Process Intensification, Chemical Engineering & Processing: Process Intensification, 2018, 148–161 (IF 2.8)

(ii) Top 5 other significant publications


(d) Synergistic Activities

- Invited speaker at several international conferences. Here are a few examples:
  - Oil and Gas Expo conference held in Dubai during 16-18 Nov15.
  - 8th International Conference on Energy from Waste, held in London during 7-8 Dec 2015
  - 4th Annual World Congress of Bioenergy, September 21-23, Qingdao, China, 2014
  - Workshop on UK-Egypt enhanced research networks in renewable energy, Feb 22-25, Egypt
- Chaired a session at the BioEnergy IV conference held during June 2-7, Otranto, Italy, 2013
- Initiator and organizer of two annual workshops at Aston University under the following titles:
  - Application of mathematical models in science and engineering held on 13 Mar 2013 and 14 Apr 2014.
  - Biomass gasification- challenges and future developments held on 18 Sep 2014.
- Acted as a reviewer for grant applications in the UK and UAE.
- Acted as external and internal examiners of more than 10 Ph.D. thesis in the UK during the period 2010-2015.
- An active member of the international scientific community in CFD modeling and biomass thermal conversion.
7.2. Co-investigator 1: Bio Sketch- Dr Gadalla (AUS)

Dr. Mohamed Gadalla
Professor of Mechanical Engineering
Department of Mechanical Engineering, American University of Sharjah, UAE
Phone #: +971 6 515-2471
Email: magadalla@aus.edu
Web page: [http://www2.aus.edu/facultybios/profile.php?faculty=mgadalla](http://www2.aus.edu/facultybios/profile.php?faculty=mgadalla)

(a) Professional Preparation
- University of Helwan, Cairo, Mechanical Engineering, B.S. (First Hons.), 1975
- University of Al-Azhar, Cairo, Mechanical Engineering, M.Sc., 1981
- University of Alabama, Tuscaloosa, Mechanical Engineering, Ph.D., 1988

(b) Appointments
- American University of Sharjah, Professor, May 2012 - present, full time
- Helwan University, Professor, 2004 - March 2006, full time, on leave
- American University of Sharjah, Associate Professor, 2000 - April 2012, full time
- Helwan University, Associate Professor, 1993 - 2000, full time
- Helwan University, Assistant Professor, 1988 - 1993, full time, on leave
- University of Alabama, Assistant Professor, 1988 - 1993, full time

(c) Publications
Top 5 most closely publications related to the proposed project

Top 5 other significant publications


(d) Synergistic Activities
- Served on the International Advisory Board of the Intersociety of Exergy, Energy and Environmental Symposium (2009-now)
- Member of the American Society of Mechanical Engineers (ASME) (1986-present)
- Member of the Egyptian engineering syndicate (1975-present)
- Member of Development Research and Technological Planning Center (DRTPC), Energy and Environmental Studies (EESU), 1993-2010, Cairo University, Egypt.
7.3.  Co-investigator 2: Bio Sketch- Dr Yehya Elsayed (AUS)

Dr Yehya Elsayed
Associate Professor - Chemistry
Department of Biology, Chemistry and Environmental Sciences (BCE)
American University of Sharjah
Tel: +971-6-5152576
Email: yelsayed@aus.edu

(a) Professional Preparation
Beirut Arab University  Beirut, Lebanon  Chemistry  B.Sc, 1997
City University of New York  New York, NY, USA  Chemistry  M.Phil. 2004
City University of New York  New York, NY, USA  Chemistry  Ph.D. 2006

(b) Appointments
• Associate Professor (2015-Present), BCE Department, AUS
• Assistant Professor (2009-2015), BCE Department, AUS
• Principal Scientist (2011), Corporate Technology, Donaldson Company Inc. (DCI), Bloomington, Mn, USA
• Senior Scientist (2006-June 2009), Corporate Technology, Donaldson Company Inc. (DCI), Bloomington, Mn, USA

(c) Publications
(i) List up to 5 publications most closely related to the proposed project

(ii) List up to 5 other significant publications, whether or not related to the proposed project


### (d) Synergistic Activities

- President, AUS Faculty Senate, American University of Sharjah (AUS), Sharjah, UAE, (2018-2019).
- Secretary, American Chemical Society International Chapter, UAE, (2018-2020).
- Member of the international scientific council of the Emirates International Forensic Conference & Exhibition, Dubai, UAE, (2015 - 2018).
- Live Interview, Sharjah TV, Harmful Effects of Midwakh, June 28, 2017.

### (e) Sabbatical Leaves awarded (give dates), internal or external grants awarded, students and post-doctoral students advised (past three years only).

- **External Grant:**
  
  1. Sofian Kanan (PI) and Yehya Elsayed (Co-PIs), Characterization of dust and debris near GCC airports, General Electric, AED 650,000 ($177,000) plus equipment (~AED 600,000 ~ $163,500), (2016-2018).

- **Internal Grant:**
  
  1. FRG 2/Regular grant (2017-2019): Development of Activated Carbon Fibers for Organic Removals” (85,000 AED or 23,160 USD)
  2. FRG 2/Regular grant (2015-2017): Adsorption of Lead and Cadmium onto Sandy Soils: Effect of Soil Particle Diameter and Competitive Adsorption” (90,000 AED or 24,460 USD)
7.4. Co-investigator 3: Bio Sketch - Dr Al-Othman (AUS)
Dr Amani Al-Othman
Assistant Professor of Chemical Engineering
American University of Sharjah
Tel: +971 6 515 2973
Email: aalothman@aus.edu

(a) Professional Preparation
Jordan Uni. of Science and Tech.  Jordan  Chemical Engineering  BSc- 2001
McGill University  Canada  Mining, Metals and Materials Eng.  MEng-2005
University of Ottawa  Canada  Chemical Engineering  PhD-2012

(b) Appointments
• American University of Sharjah, Assistant Professor, Sep. 2013-Present
• Graduate Academic Advisor, Saudi Cultural Bureau/Royal Saudi Embassy, Ottawa, 12-13.
• Teaching Assistant, Undergraduate Courses, University of Ottawa, 2008-2012.
• Research Assistant, University of Ottawa, 2007-2012.
• Research Assistant, Mineral Processing, McGill University, 2005-2006.
• Graduate Teaching Assistant, McGill University, 2002-2005.

(c) Products
(i) Journal publications
• Hanin Mohammed; Amani Al-Othman; Paul Nancarrow, Ph.D.; Yehya Elsayed; Muhammad Tawalbeh, Zirconium phosphate/ionic liquids proton conductors for proton exchange membrane (PEM) fuel cells operating at elevated temperatures, submitted to Scientific Reports, 2018 (under review).

Amani Al-Othman, André Y. Tremblay, Wendy Pell, Sadok Letaief, Yun Liu, Brant A Peppley, Marten Ternan, “Modified Silicic Acid (Si) and Sulphuric Acid (S)-ZrP/PTFE/Glycerol Composite Membrane for High Temperature Direct Hydrocarbon Fuel Cells”, *Journal of Power Sources*, 224 (2013) 158-167.

(ii) Talks and presentations


(d) Synergistic Activities

- Served as a technical review committee member at the Eleventh International Conference on Composite Science and Technology (ICCST/11), American University of Sharjah, (2016).
7.5. Co-investigator-4: Bio Sketch- Dr Lyra (ICBA, Dubai)
Dr Dionysia-Angeliki Lyra
Halophyte Agronomist
International Center for Biosaline Agriculture, Dubai, United Arab Emirates
T +971 4 3361100 ext.261
M +971 56 5052479
F +971 4 3361155
E-mail: d.lyra@biosaline.org.ae
Web page: https://www.biosaline.org/

(a) Professional Preparation
Undergraduate Institution Agricultural Uni of Athens, Greece Agriculture Eng., 2001
Graduate Institution, Agricultural Uni of Athens, Greece, Crop Science, Biotic stress, MSc 2003
Postdoctoral Institution, Agricultural Uni of Athens, Greece, Drought-tolerant crops, PhD 2009
Postdoctoral Institution, Agricultural Uni of Athens, Greece, Highly Salt-tolerant crops 2013-15

(b) Appointments
In reverse chronological order, list the individual’s academic/professional appointments.
- Halophyte Agronomist
- Research Assistant at the Laboratory of Agronomy at the Agricultural University of Athens
- Employee at the Hellenic Ministry of Agriculture
- Extension officer at the Directorate of Agriculture in Southern Greece

(c) Publications
List up to five (5) products most closely related to the proposed project
4) S. M. Robertson, D. Lyra, J. Mateo-Sagasta, S. Ismail and M. J. U. Akhtar (In press), Financial analysis of halophytes cultivation in a desert environment using different saline water resources for irrigation In: Ecophysiology and utilization of halophytes under changing environment, Editor: Mirza Hasanuzzaman. Springer Japan

(i) List up to five (5) other significant products


**(d) Synergistic Activities**

- Organized a volunteer program for HSBC employees in collaboration with AUC/RISE in Egypt who were trained on sustainable agriculture practices. (2016-2018) Location: ICBA, Dubai, UAE.
- Organized and participated as a speaker at MENA NWC Workshop on “Innovative technologies and Integrated Solutions to improve water and soil use efficiency under arid conditions” Location: ICBA, Dubai, UAE.
- Organized a training program to educate extension officers from Abu Dhabi Farmers Service Centre on Biosaline Agriculture Technologies, Location: Al Ain, Dubai, U.A.E.
- Organized a workshop to train extension officers on “Enhancing small scale irrigation technologies and management in saline areas in Africa (English), Locations: Dubai & Ghana. This training was funded by BADEA.
7.6. **Co-investigator-5: Bio Sketch- Dr Masek (UoE)**

**Dr Ondřej Mašek**

Lecturer in Engineering Assessment of Biochar  
School of GeoSciences, University of Edinburgh, Edinburgh, UK  
Web page: [https://www.ed.ac.uk/geosciences/people?indv=2113](https://www.ed.ac.uk/geosciences/people?indv=2113)

(a) **Professional Preparation**

- **VŠB- Technical University of Ostrava, Ostrava, Czech Republic**  
  M.Sc. - Energy  
- **Hokkaido University, Japan, Material Engineering**  
  PhD 2007

(b) **Appointments**

<table>
<thead>
<tr>
<th>Position</th>
<th>Institution</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lecturer</td>
<td>University of Edinburgh</td>
<td>2009–present</td>
</tr>
<tr>
<td>Postdoctoral Research Fellow</td>
<td>Cranfield University</td>
<td>2007–2009</td>
</tr>
</tbody>
</table>

(c) **Publications**

Top five most closely publications related to the proposed project


5. Ghidotti, M., Fabbri, D., Mašek, O., Mackay, C.L., Montalti, M., Hornung, A. Source and Biological Response of Biochar Organic Compounds Released into Water; Relationships with Bio-Oil Composition and Carbonization Degree, (2017) Environmental Science and Technology, 51 (11), pp. 6580-6589.

(ii) Top five other significant publications


(d) Synergistic Activities
- Research networks: Masek is a work package leader in an EU-funded innovative training network “GreenCarbon”, and he also leads the Royal Academy of Engineering project “Accelerating biomass-based polygeneration in Indonesia - sustainable fuels, chemicals and materials” (2017-2019). He has been a management committee member and a country representative on two COST Actions (FP1306- Lignoval, and CA17128-LignoCOST). He has also let University of Edinburgh’s contribution to ERDF-funded “Scottish Biofuels Resource Centre” between 2012 and 2015 assisting SMEs with development of new biomass-based products and services.
7.7. Co-investigator 6: Bio Sketch - Hossain (AU)
Dr Abul Kalam Hossain CEng FHEA MEI
Lecturer in Mechanical Engineering and Design,
Sustainable Environment Research Group
Aston University, Birmingham, UK.
http://www.aston.ac.uk/eas/staff/a-z/dr-abul-hossain/
https://www.researchgate.net/profile/A_Hossain/contributions

(a) Professional Preparation
Postgraduate Certificate in Professional Practice (PGCPP) - Aston University, UK (February 2014)
PhD in Mechanical Engineering - Cranfield University, UK (June 2006)
MSc (by research) - Cranfield University, UK (June 2002)
BSc in Mechanical Engineering with 1st Class – Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh (November 1993)

(b) Appointments
2014 –Present: Lecturer, Mechanical Engineering and Design Group, Aston University, UK
2007 – 2013: Research and Teaching Fellow, Aston University, UK.
2000 – 2006: MSc and PhD Researcher, Cranfield University, UK
1994 – 2000: Mechanical Engineer (in industry)

(c) Publications
Top five most closely publications related to the proposed project

(ii) Top 5 other significant publications


(d) Synergistic Activities
Chartered Engineer (CEng), Member of the Energy Institute (MEI)
Fellow of the Higher Education Academy, UK (FHEA)
Member of the UnICEG
Member of the PhD Examination – Anna University, Chennai, India
Member of the Scientific Advisory Committee, 13th and 14th SDEWES
Chaired technical session at the 13th SDEWES conference (29 Sep – 04 Oct 2018)
Keynote, Invited Lecture (selection):
7.8. Co-investigator-7: Bio Sketch- Prof Ocone (HWU)

Prof Raffaella Ocone
Chemical Engineering
School of Engineering and Physical Sciences
Heriot-Watt University
Edinburgh EH14 4AS, UK
Tel. (+44) (0) 131 451 3777; Email: r.ocone@hw.ac.uk

(a) Professional Preparation
- Princeton University, Princeton, NJ, Ph.D., Chemical Engineering, April 1992
- Ateneo Federiciano, Università di Napoli Federico II, Italy, Chemical Engineering, June 1987

(b) Appointments
(1995 - present) Professor of Chemical Engineering, Heriot-Watt University, UK
(1995-1999) Reader in Chemical Engineering –University of Nottingham, UK
(1992-1995) Lecturer –Chemical Engineering, University of Naples, Italy
(1987-1991) PhD Student –Chemical Engineering, Princeton University, USA
(1985-1987) Research Student –Chemical Engineering, University of Naples, Italy

(c) Products
Published more than 90 papers, here below the latest 10 papers


(d) Synergistic Activities
- Fellow of the Royal Academy of Engineering, 2013
- Fellow of the Royal Society of Arts, 2009
- Cavaliere (Nightood) of the Order of Merit, Italian Republic, 2006
- Fellow of the Royal Society of Edinburgh, 2006
- Fellow of the Institution of Chemical Engineers, FIChemE
- Fellow of the Royal Society of Chemistry, FRSC
- Chartered Engineer, CEng
- Chartered Scientist, CSci
- Member of the "EPSRC Peers College", 1999-present
- External Examiner, MSc in Advanced Chemical Engineering and MSc in Chemical Engineering with Design, The University of Manchester, 2013 -2016
- External Examiner, Meng Chemical Engineering, Imperial College London, 2013 -present
- External Examiner, BEng and Meng Chemical Engineering, Newcastle University, 2014-pres.
7.9. Co-investigator 8: Bio Sketch- Davies (AU)
Prof Philip Davies
Head of Group and Reader in Mechanical Engineering and Design
Aston University, Birmingham, UK
Mobile: +44 7866 802603
E-mail: p.a.davies@aston.ac.uk

(a) Professional Preparation
2007 Postgraduate Certificate in Learning and Teaching for Higher Education
1990 Doctoral Thesis (D.Phil), Green College, University of Oxford
1984 B.Sc.(Eng), 1st Class and 3 prizes, Mechanical Engineering, Imperial College, London

(b) Appointments
2017 Head of Department & Associate Dean Training Course, Aston University
2012 Influencing and Negotiating, John Ramsden Associates, at Aston University
2011 Life Cycle Assessment made easy with Simapro, Intertek, London
2008 Basic TRIZ, Oxford Creativity, Oxford
2004 FLOVENT Introductory Training Course, Flomerics, London
2002 Certificate in Business Language Competence (Operational, French) OCR
2001 Consulting with Clients, Excel Communications Ltd, Cambridge

(c) Products
Published more than 80 papers, here below the relevant papers


8. SUPPLEMENTARY DOCUMENTS

a. Course release summary

Dr Makkawi (PI)

Dr. Makkawi, is requesting 3-course release over the period covered by this project (2019-2022). He is currently leading two externally funded research projects in addition to two internally funded projects as detailed below:

- Project 1:
  Title: Production of acidic biochar (PI: Makkawi)
  Duration: 2018-2020
  Fund source: EGA industry (Emirates Global Aluminium) - AED 665,000

- Project 2:
  Title: Solar-thermal conversion of waste to energy (PI Makkawi)
  Duration: 2018-2019
  Fund source: GSIKE and British Council (UK) - AED 100,000

- Project 3:
  Title: Sustainable production of biofuels from the Arabian Gulf Algae (PI Makkawi)
  Duration: 2018-2020
  Fund source: AUS FRG - AED 149,000

- Project 4:
  Title: A novel thermochemical conversion of paper industry wastes to fuel gas (PI Makkawi)
  Duration: 2018-2019
  Fund source: AUS FRG - AED 75,000

In addition to the above, the PI is awaiting decision on a new proposal as detailed below

- Project 5:
  Title: Utilization of desalination brine for bioenergy and carbon sequestration (PI Makkawi)
  Duration: 2019-2021
  Fund source: GSIKE and British Council - AED 610,000

Dr Gadalla (Co-I 1)

Dr. Gadalla is requesting 1-course release over the period covered by this project (2019-2022).

Dr Elsayed (Co-I 2)

Dr. Elsayed is requesting 1-course release over the period covered by this project (2019-2022).

Dr Amani (Co-I 3)

Dr. Amani is requesting 1-course release over the period covered by this project (2019-2022).
b. Letters of commitment

Letter of commitment: International Center for Biosaline Agriculture (ICBA) - Dubai

Letter of commitment

Date: 24-10-2018
Ref: ICBA/DG/10/18/0154D

From: Dr. Ismahane Elouafi
Title: Director General
Organization: International Center for Biosaline Agriculture (ICBA)

To: Dr. Yassir Makkawi
Department: Chemical Engineering
Organization: American University of Sharjah (AUS)

Subject: Participation in a Project funded by AUS

This letter of commitment is to confirm ICBA’s participation in the project entitled “A Novel Bioenergy System for Marginal Environments”. The project is at the stage of proposal writing and the deadline for submission is 28th of October. ICBA will grow different Salicornia genotypes with seawater, saline groundwater, the reject brine from desalination and aquaculture effluents. Salicornia biomass and seed samples will be given to Dr. Yassir Makkawi to study the bioenergy potential of this halophytic species which has great adaptability in desert environments. Salicornia has great prospects as a feedstock for biofuel and has been field tested at large scale at ICBA’s experimental station and at a coastal desert area under the harsh desert environment in the UAE for more than 5 years.

The main goal of this project is to provide a proof of concept for a cost effective and technically feasible modern bioenergy system through theoretical modelling, thermo-economic and experimentation analyses and a demonstrated test rig. The proposed project duration is 36 months with a total budget of AED 995,000. The project consortium will include, in addition to the AUS researchers, international collaborators from three different reputed universities in the UK with expertise in solar thermal conversion and bioenergy technologies.

ICBA is highly supportive of the efforts outlined in this proposal in order to help in achieving the “UAE Vision 2021 and 2050” for waste minimization and the set target for 44% energy from renewable resources.

Yours sincerely,

Dr. Ismahane Elouafi
Director General
Letter of commitment: Aston University (AU)- UK

Aston University

American University of Sharjah (AUS)
PO Box 26666, Sharjah, UAE

24th October 2018

Re: Aston University - American University of Sharjah (AUS) Research Collaboration ‘A Novel Bioenergy System for Marginal Environments’

It is a pleasure to support the Aston-AUS research collaboration project application to the American University of Sharjah (AUS), UAE. There is great synergy between the research activities of American University of Sharjah, and those of Aston University. Both institutions have interests in development of sustainable technologies to provide energy based on novel conversion approaches. This project is a natural development of work done at Aston and AUS, some of that being conducted under the project ‘Solar-thermal conversion of waste to energy’, funded by British Council under Gulf Science Innovation and Knowledge Economy (UK and Gulf) stream.

The aim of the proposed project is to develop sustainable novel bioenergy solutions for UAE. The project in particular would help in achieving the UAE’s 44% renewable energy target by 2050. The proposed research would involve Dr Philip Davies, Reader and Dr Aziz Hossain, Lecturer in Mechanical Engineering and Design (School of Engineering and Applied Science, Aston University) in collaboration with Dr Yaser Makkawi, Associate Professor, Department of Chemical Engineering, American University of Sharjah, UAE. Dr Davies would be involved in the design and modifications of a solar collector and tracking system. Dr Hossain will be working on the characterisation, optimisation and engine testing of the novel fuels to be produced in UAE.

The project is of particular interest to Aston University, as it will help us to fulfil strategic goals, through promoting our reputation and visibility internationally and carrying out translational research with high social and economic impact. The relationship with our institutions engaged in research and teaching will be very much welcomed as a way to strengthen our international networks.

On behalf of Aston University, I am happy to accept the terms and conditions associated with this award (should it be successful) and confirm our willingness to administer the funds as defined in the relevant grant agreement.

Yours faithfully,

Professor Sarah Hainsworth
Executive Dean
School of Engineering and Applied Science
Tel 44 (0) 121 204 3945
shainsworth@aston.ac.uk
Letter of commitment: University of Edinburgh (UoE)- UK

Dear Panel Members,

RE: American University of Sharjah (AUS) Faculty Research Grant 2019 funding proposal 'A Novel Bioenergy System for Marginal Environments' led by Dr. Yassir Makkawi

I am writing to express my full support for the proposal and commitment of the School of Geosciences to participate in the project.

The University of Edinburgh has global reach, ambition, commitment and capability which makes it an ideal partner in the. Our global reach is demonstrated by 260 partners in 46 countries and the fact that 43% of Edinburgh’s students come from outside the UK. Our ambition is expressed in our global strategy, which includes investment in five Global Academies that cross boundaries between research and teaching, and stimulate multidisciplinary responses to challenging global issues. The University has a deep and sustained commitment to international development and in February 2018 we signed the UN Sustainable Development Goals Accord. We have globally-leading expertise in the field of international development research and a proven track record in successful operationalising and delivering highly complex projects. This proficiency encompasses many topics and reflects equitable partnerships in many developing countries. The School of Geosciences (UK top 3 in REF2014), in particular, has laid strong foundations and demonstrated its capability by attracting over £2.7M ODA compliant funding from GCRF funding, but also Newton Fund and other schemes since 2016.

Contribution of the University of Edinburgh will be coordinated by Dr. Ondřej Mašek (leader of pyrolysis research group at the School of Geosciences). In addition, University of Edinburgh will provide access to its unique pyrolysis (laboratory and pilot-scale) and analytical facilities to be used by the project at standard research rates. This proposal is directly aligned and synergistic with the University’s and the School of Geoscience’s strategy of excelling in the provision of a unique, interdisciplinary blend of fundamental and applied research to tackle global trends of rapid urbanisation and climate change on sustainable development and sustainable resources management in high and low-income countries.

Yours faithfully,

S. P. Kelley
Prof. Simon Kelley
Head of the School of Geosciences
University of Edinburgh
Letter of commitment: Heriot-Watt University

To: Dr. Yassir Makkawi  
Department: Chemical Engineering  
Organization: American University of Sharjah (AUS)

Professor Robert Reuben  
Head of Institute of Mechanical, Process and Energy Engineering  
School of Engineering & Physical Sciences  
Heriot-Watt University  
Edinburgh EH14 4AS

Tel: +44-131-451-3615  
R.reuben@hw.ac.uk

28 October 2018

Dear Dr Makkawi,

Subject: Participation in a Project funded by AUS

This letter confirms the intention of Heriot-Watt University (HWU) to participate in the AUS project entitled “A Novel Bioenergy System for Marginal Environments”.

As I understand it, the main goal of this project is to provide a proof of concept for a cost effective and technically feasible modern bioenergy system through theoretical modelling, thermo-economic, experimentation analyses and a demonstrated test rig. The proposed project duration is 36 months with a total budget of AED 995,000. The project consortium will include, in addition to the AUS researchers, international collaborators from three different well-renown universities in the UK with expertise in numerical modelling, solar thermal conversion and bioenergy technologies.

I am pleased to confirm that Professor Raffaella Ocone will provide help with the numerical modelling and simulation work, by employing the techniques that she has developed for simulating the hydrodynamics and the kinetics in multiphase flow systems. The model will provide a design tool which will help understand the proof of concept and its capabilities to be scaled up.

HWU is highly supportive of the efforts outlined in the proposal to achieve the "UAE Vision 2021" for waste minimisation and the set target for 44% energy from renewable resources by 2050.

Yours sincerely,

[Signature]

Prof Robert Reuben  
Head of IMPEE

Institute of Mechanical, Process and Energy Engineering  
School of Engineering and Physical Sciences  
James Nasmyth Building, Colt 3  Heriot-Watt University  Edinburgh EH14 4AS  United Kingdom  
Telephone: +44 (0)131 449 5111  www.eps.hw.ac.uk

Edinburgh Campus • Scottish Borders Campus • Orkney Campus • Dubai Campus
Heriot-Watt University is a Charity registered in Scotland, SC000278
c. Letters of Support
Souq Al-Jubail-Sharjah

Dr. Yasir Makkawi
Department of Chemical Engineering
American University of Sharjah

Ref. No.: SAM-SEP-001-LTE-08
Date: 20th Oct 2019

Dear Dr. Makkawi


Following a series of discussions and looking at the planned research project for a novel pyrolysis and gasification system using solar thermal energy, we would like to express our interest in supporting this project.

Souq Al Jubail is one of the largest fresh produce markets in the UAE and as a part of our role in the environmental sustainability and social responsibility towards Emirates of Sharjah and its residents, we are very pleased to support your project. As per the Government of Sharjah guidelines for clean and healthy environment, Souq Al Jubail is interested in participating in sustainability & renewable energy research & applications.

The proposed use of food waste as a feedstock for biofuels production and the integration of the process with solar energy fall in line with the UAE 2021 vision for renewable energy and waste minimization. Here, in Souq Al Jubail, we are currently exploring economically viable and environmentally friendly solutions for the disposal of more than 10 ton/day of food waste produced on daily basis at our fruit & vegetable, meat and fish market.

Having looked at the various solutions during the past few years, we believe that the proposed thermochemical conversion of this waste to biofuel and biochar may be a good solution to handle our daily produced waste. If realized, this will be of benefit to reduce our reliance on conventional fuel, while generating another line of revenue by selling the by-product biochar as a fertilizer. We also have an interest in utilizing the product gas to aid in running the newly constructed Grilling section in Souq Al Jubail.

Moreover, we believe the outcome of this project will contribute to the local and global effort in developing new renewable energy technology and reducing greenhouse emissions.

We can provide various types of biomass food waste and be involved in supporting the project. We also propose to attend regular meetings (as an advisory role), assisting in publicizing the project and outcome to the local media and through our media channels.

Yours Sincerely,

Eng. Mansel Al Zarooni
Director - Souq Al Jubail Sharjah Asset Management Holding (SAMA)

Souq Al Jubail, UAE
P.O. Box 4019, T: +971-6-518-4181, F: +971-6-518-0217, Sharjah, United Arab Emirates
www.souqaljubail.com
d. Collaboration plans

It is proposed that the PI will have face-to-face meetings with the AUS researchers on a weekly basis; while meetings with the external collaborators will be conducted during the exchange visits, and more frequently via emails and phone conference. Remote access to a main computer will be facilitated, where all parties can have access to the updated experimental and modeling results at all stages during the project execution. The collaboration and implementation plan of the WPs described in Section 4.7 are given below.

Co-investigator 1: Dr Mohamed Gadalla (American University of Sharjah, AUS).
Dr Gadalla (AUS) has extensive experience in hybrid renewable energy technologies, fuel cells, concentrated solar power and thermo-economic analyses. In this project his contribution will be on the design, construction and commissioning of a parabolic trough with tracking system and tubular receiver/reactor. He will also be closely working with the collaborators from Aston University (AUS) on the thermo-economic assessment and with the PI on integration of the reactor and preparation if the infrastructure for the demonstration rig. AUS MSc students will deliver the results, under the supervision of Prof Gadalla, as MSc thesis report.

Co-Investigator 2: Dr Yehya Elsayed (American University of Sharjah, AU, AU).
Dr Yehya will be contributing to the project activities defined in WP5 and WP6 by carrying out the chemical analysis of the biomass feedstocks, biofuels and biochar. This will be facilitated through accessing a range of instrumentation available at the AUS Biology, Chemistry and Environmental Sciences Department (e.g. GC-MC, ICP, TGA...etc.). In doing so, Dr Elsayed will be directly working with the AUS postdoc researcher and MSc students 1.

Co-Investigator-3: Dr Amani Al-Othman (American University of Sharjah, AUS)
Dr Amani will take the responsibilities of setting the experiment with solid oxide fuel cell and its performance evaluation by measuring the current and potential difference across the cell while in operation. This will monitor the chemical reactions occurring inside the fuel cell upon the introduction of the hydrogen-rich gas. Dr Amani’s contribution will also feed into the overall process thermo-economic (WP 8).

Co-Investigator 4: Dr Dionysia Aggeliki Lyra (International Center for Biosaline Agriculture, ICBA).
Dr Lyra (ICBA) will be in direct collaboration with the PI. She will be in charge of the growth and supply of Salicornia. This will involve growing different genotypes of the plant at ICBA facilities irrigated with seawater, ground saline water, water include reject from desalination and aquaculture effluent. Upon pyrolysis and gasification, Dr Lyra will contribute to mapping the quality of the product biofuels and char with the halophyte species and cultivation condition. This will contribute to overall optimization of the proposed bioenergy system and its future exploitation at large scale processing.

Co-Investigator 5: Dr Ondrej Masek (University of Edinburgh, UoE)
Dr Masek will be collaborating on WP4 and WP5 by contributing to the analysis of the particulates produced in the pyrolysis and gasification. In particular, his contribution will be focused on the planar optodes experiments at Edinburgh University to analyse the gasification biochar/ash in
terms of the interaction of O$_2$, pH and CO$_2$ with the soil. He will also work closely with the PI to identify optimum pyrolysis experiments for tailored biochar qualities.

Co-Investigator 6: Dr Abul Hossain (Aston University, AU)
Dr Hossain is an experienced researcher in developing sustainable renewable energy systems and combustion and emission characteristics of alternative fuels in internal combustion (IC) engines. He will carry out experimental investigation of the performance and emission in a multi-cylinder CI engine fuelled by pyrolysis oil or its blends with biodiesel. This will also include analysis of the bi-oil flash point, cetane number, iodine number, ash content and carbon residue. The PI and the AUS co-investigator, Dr Elsayed, will provide Dr Hossain samples of the pyrolysis and its characteristics.

Co-Investigator 7: Prof Raffaella Ocone (Heriot-Watt University, HWU)
Prof Ocone (HWU) will contribute to the development of new models for carbon capture and tar cracking based on the chemical characteristics of the biomass to be investigated. These models will then be implemented by the PI in a full predictive model to simulate the thermochemical behaviour of pyrolysis reactor and gasifier. The proposed CFD work provides a robust tool for parametric analysis and scale-up analysis of the novel bioenergy system. This project will benefit from the extensive experience and previous collaboration between the PI and Prof Ocone in developing mathematical models for fluidized bed reactors and biomass pyrolysis.

Co-Investigator 8: Prof Philip Davies (Aston University, AU),
Prof Davies (AU) will be directly collaborating with the AUS co-investigator, Prof Gadalla on the identified activities under WP 3, WP 7 and WP 8. He will also take the role of advising on the installation of the outdoor installation of the final closed loop system. Dr Davies has invaluable experience in collaborations and applications of renewable energy and water technology in marginal environments including the Middle East, North Africa and the Indian sub-continent. Besides, he will be currently collaborating with the PI in another related project on solar thermal conversion and he will be visiting the AUS on frequent basis.

**e. Data Management plans**
The collaborators are developing an ambitious and highly novel bioenergy technology. The PI will take the responsibility of data collection and storage in a computer. Access to this data will be password protected. For Intellectual property (IP) and data protection, all the project team will sign collaboration and IP agreements in accordance to the AUS policies.

**f. Results dissemination plan**
The results will be published in national and international top-class journals and conferences. The identified appropriate journals include the ACS sustainable chemistry and engineering (IF 6.1), Biomass and Bioenergy (3.3), Fuel (4.6), Energy Conversion and Management (IF 6.3), Renewable Energy (IF 4.9) and International Journal of Hydrogen Energy (IF 3.6). Example of the appropriate conferences will be on Biofuels, Bioenergy, Biochar, Renewable Energy and Solar-Thermal Conversion. Further dissemination will be through a website, workshop and local public media (TV channels and newspapers). Within AUS, the project team will arrange two presentations to the faculty and MS students.